

Buoyancy Effects on Flow Transition in Hydrogen Gas Jet Diffusion Flames

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Abstract

Experiments were performed in earth-gravity to determine how buoyancy affected transition from laminar to turbulent flow in hydrogen gas jet diffusion flames. The jet exit Froude number characterizing buoyancy in the flame was varied from 1.65×10^5 to 1.14×10^8 by varying the operating pressure and/or burner inside diameter. Laminar fuel jet was discharged vertically into ambient air flowing through a combustion chamber. Flame characteristics were observed using rainbow schlieren deflectometry, a line-of-site optical diagnostic technique. Results show that the breakpoint length for a given jet exit Reynolds number increased with increasing Froude number. Data suggest that buoyant transitional flames might become laminar in the absence of gravity. The schlieren technique was shown as effective in quantifying the flame characteristics.

Introduction

Transition from laminar to turbulent flow in diffusion flames has been a subject of study for many years. Transitional flame research began with the classic work by Hottel and Hawthorne [1]. They conducted experiments using different fuels in ambient air to determine the range of the cold jet Reynolds number when the transition occurred. Using hydrogen, they determined that the flame transitioned at cold jet Reynolds numbers (Re) between 1300 and 2250. At the onset of transition, the flame consists of two distinct regions; a laminar-region near burner and a turbulent region at the top of the flame. The axial location where the laminar and turbulent regions meet was called the envelope of breakpoint, which was stable. As the jet velocity was increased, the distance between the burner exit and breakpoint decreased faster than the flame height. When the flame height became independent of the jet velocity, the breakpoint approached the burner, indicating a fully developed turbulent flame.

As research progressed, it was determined that the transition from laminar to turbulent combustion is associated with changes in the structure of the fuel jet. According to Coats and Zhou [2], the transition process can be triggered in two different ways: by the instabilities in the shear layer of the fuel jet or by flow fluctuations inside the burner port. The instabilities in the shear layer of the fuel jet are directly related to the cold jet Reynolds number of the fuel, whereas the flow fluctuations at the burner port are determined from the type of burner. Takeno and Kotani [3] observed these transition mechanisms in flames from long tube burners with fully developed flow. To explain this observation, they defined a flame Reynolds number that used the kinematic

viscosity of the gas at flame temperature instead of that at the jet exit temperature. The authors suggested that the critical flame Reynolds number for transition by fuel jet instability is 227. Similar observations were made by Takahashi et al. [4], who studied the transition behavior of hydrogen and nitrogen-diluted hydrogen flames using tube burners.

A great deal of the transitional flame research has aimed at determining the differences between the cold jet and the flame. It is known that the transition process is delayed in flames because heat-release in the flame laminarizes the fuel jet [5]. This effect has been attributed to several factors. Yule et al. [5] attributed it to a higher kinematic viscosity, which lowers the local Reynolds number. Clemens and Paul [6] provide evidence that the lengthening of the potential core is due to the high density ratio in the flame, which reduces the growth rate of the jet shear layer. Katta and Roquemore [7] performed numerical simulations to conclude that buoyancy produced longer potential core in flames as compared to that in cold jets. They explained that the acceleration of the hot gases in the flame by buoyancy entrains fluid that would normally be in the inner vortices of the jet shear layer. This causes the inner vortices to dissipate rapidly in a flame.

Since buoyancy was determined to influence the flame, Hegde et al. [8] conducted experiments at NASA's 2.2-second drop tower to observe the difference in flame characteristics at normal gravity and microgravity. Flames in microgravity experience virtually no buoyancy since gravity is nearly zero. They found that flames in microgravity are taller and wider than those in earth gravity. In microgravity, the flame height increases in the transitional region unlike the observations in earth

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gravity. They attributed this effect to the smaller effective diffusivity of transitional flame in microgravity than that in earth gravity. It was concluded that the transition process occurs over a wider range of Reynolds numbers in microgravity flames since there is no buoyancy-generated turbulence [8].

In this study, we investigate buoyancy effects on flame transition in momentum-dominated hydrogen-jet diffusion flames. We focus on the transition mechanism arising from instability in the fuel jet. Thus, the jet exit Reynolds number was kept below the critical Reynolds number for turbulent pipe-flow. The buoyancy was controlled by varying the operating pressure and/or burner diameter in an earth based facility. The flame characteristics were observed using Rainbow Schlieren Deflectometry or RSD, a line-of-sight optical diagnostics technique. A second objective of the study was to demonstrate the effectiveness of the RSD technique in quantifying the flame characteristics. In the following sections, we describe the experimental setup, and present results, discussions, and conclusions.

Experimental Setup

Experiments were conducted in a continuous flow combustion chamber with a 0.75m high stainless steel test section of 0.3m x 0.3m cross-section as shown in Fig. 1. The optical access was provided by flat, tempered glass windows (0.2m x 0.6m and 10mm thick) on parallel side-walls. The fuel to the tube burner was supplied from a compressed gas cylinder, regulated by a needle valve and measured by a calibrated mass flow meter. Nearly quiescent co-flow air was accomplished in the test-section by filling an upstream diffuser with glass marbles followed by flow straightener and a section of aluminum foam. The co-flow air was supplied by an air-compressor, regulated with a pressure regulator, and measured using a calibrated rotameter. The downstream end of the test-section was connected to vacuum pump with inlet valves to control the airflow and pressure in the chamber. The flame was visualized using rainbow schlieren apparatus set up on an optical breadboard shown in Fig. 2 that was mounted rigidly onto the combustion chamber [9, 10]. In

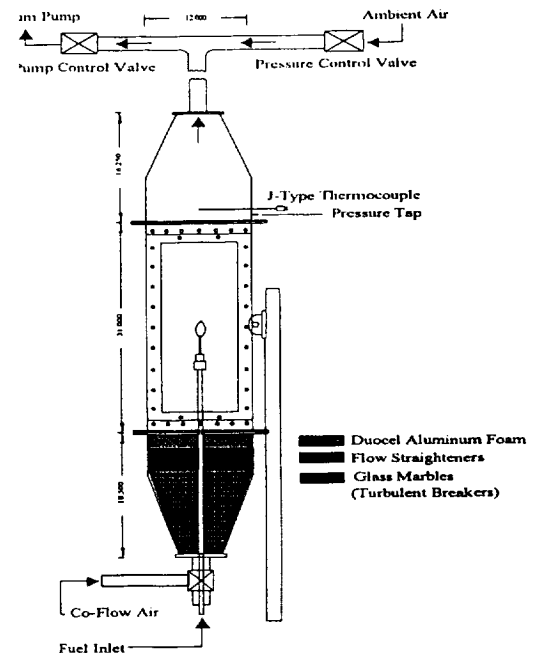


Figure 1. Schematic Diagram of the Test Facility

this system, a continuously graded 12-mm wide, symmetric color filter was placed at the focal point of the decollimating lens with effective focal length of 3480mm. The color schlieren images were acquired by a 3-chip CCD camera, and recorded in the S-VHS format. The quantitative analysis was performed with a set of 100 consecutive frames digitized by a 24-bit color frame grabber. The digitized frames were stored as 640 x 480 pixel files in TIFF format. Two 1/60th second apart field images were recovered from each frame. The field-of-view was limited to about 40mm from the burner exit. The spatial resolution in the experiment was about 0.06mm.

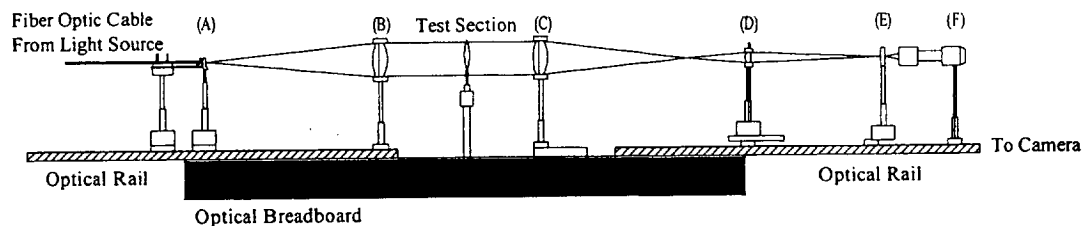


Figure 2. Optical Configuration of the Rainbow Schlieren Apparatus. (A) aperture, (B) collimating lens, (C) decollimating lens, (D) magnification lens, (E) rainbow filter, (F) camera lens.

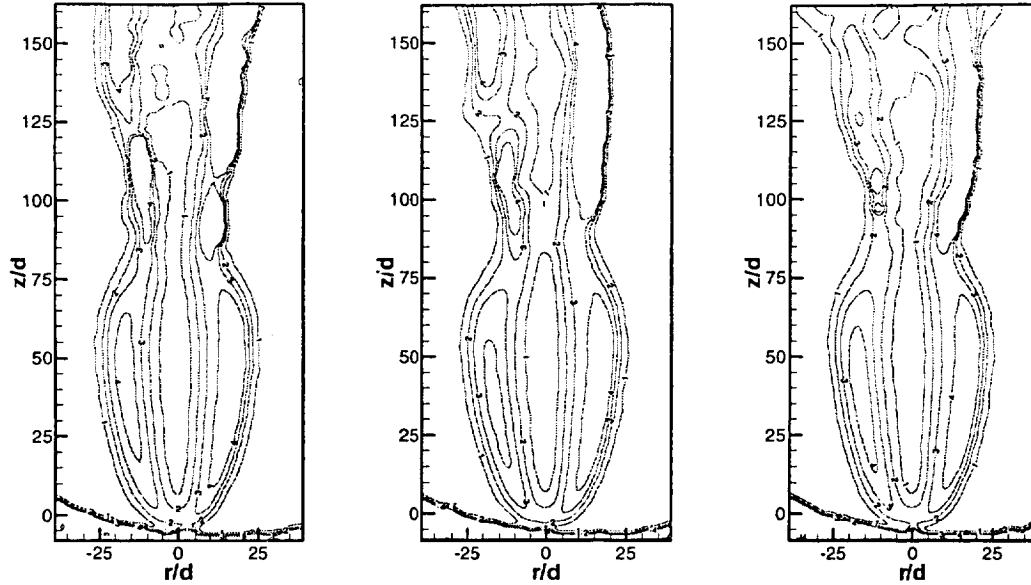


Figure 3. Contours of Instantaneous Angular Deflection, Images are 1/30th of a Second Apart, $d=0.305\text{mm}$, $P=1.0\text{ atm}$, $Re=1700$

Results and Discussion

Experiments were conducted by varying the jet exit Froude number (Fr) to determine how buoyancy affected the transition from laminar to turbulent combustion. Here, $Fr = v^2/gd$, where v is the jet exit velocity, g is the gravitation acceleration on earth, and d is the burner inside diameter. For a given Reynolds number, the Froude number was varied by using different diameter burners, and by varying the operating pressure.

Flame Characteristics. The schlieren images were used to determine the angular deflection, given as the refractive index (or density) gradient integrated along the line-of-sight. Figure 3 shows contour plots of angular deflection obtained from a sequence of three instantaneous images that are 1/30th of a second apart. The contour levels are in 1/100th of a degree (e.g. level 3 represents an angular deflection of 0.03 degrees). In the three contour plots, the breakpoint is located approximately at $z/d=90$, where the flame width is a minimum. In the laminar region at $z/d < 90$, the angular deflection contours appear steady. At $z/d > 90$, the angular deflection contours show random variations.

Instantaneous details presented above do not represent all of the characteristics of the flame because of the random 3D fluctuations. In such cases, time statistics are more accurate for comparing experimental data and modeling predictions [11]. Therefore, the contour plots of mean and rms angular deflection were created from 200 consecutive field images taken over 3.33 seconds. Figure 4 illustrates contour plots of the mean and rms angular deflection in a transitional flame with $d=0.305\text{mm}$, $P=1.0$

atm , and $Re=1700$. As expected, the contour plot of mean angular deflection is nearly symmetric. The contour plot of rms angular deflection in Fig. 4 shows that fluctuations are confined to the turbulent region of the flame. Figure 5 illustrates contour plots of mean angular deflection for $Re=1500$, 1700 , and 2100 with $d=0.305\text{mm}$ and $P=1.0\text{ atm}$. Evidently, the breakpoint length decreased as the Reynolds number increased. In Fig. 5, the breakpoint is located at $z/d \approx 135$, 90 , and 50 , respectively, for Reynolds numbers of 1500 , 1700 , and 2100 .

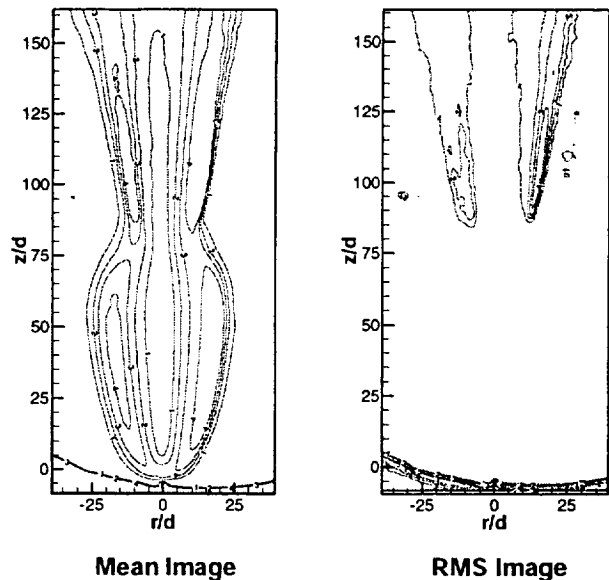


Figure 4. Contours of Mean and RMS Angular Deflection, $d=0.305\text{mm}$, $P=1\text{atm}$, $Re=1700$.

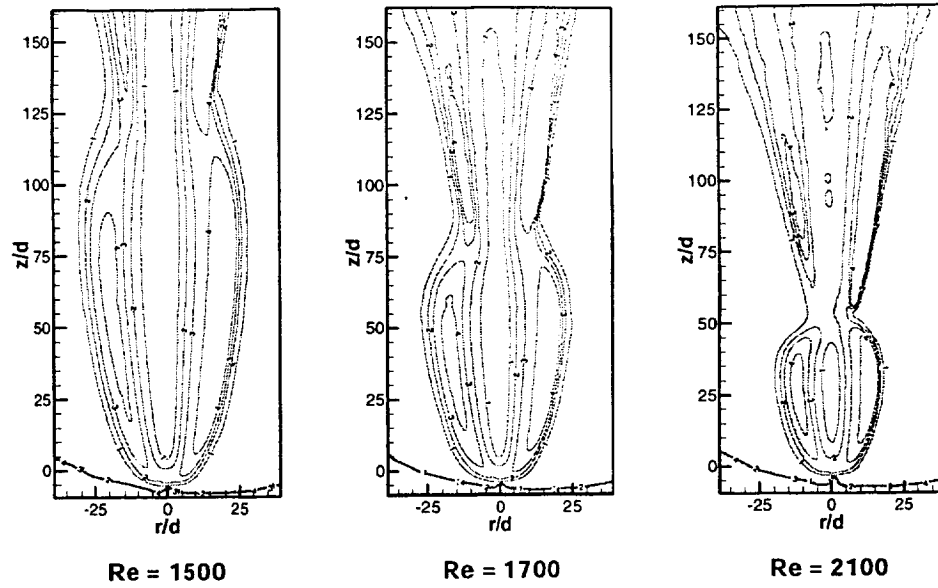


Figure 5. Effect of Reynolds Number on Contours of Mean Angular Deflection, $d=0.305\text{mm}$, $P=1\text{ atm}$.

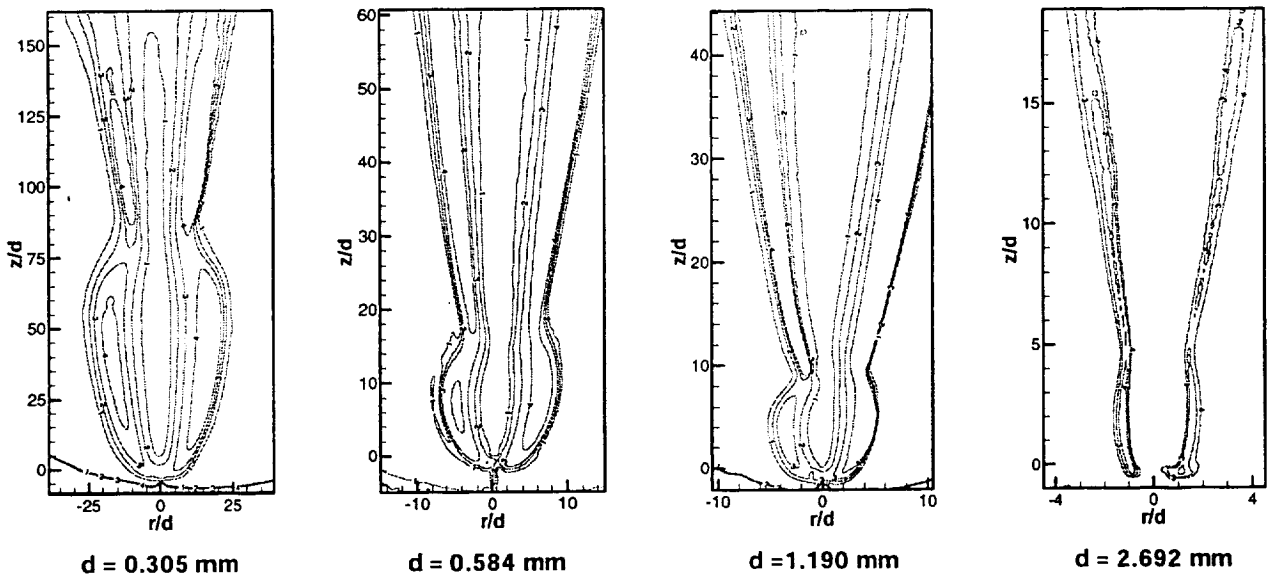


Figure 6. Effect of Burner Diameter on Contours of Mean Angular Deflection, $P=1\text{ atm}$, $Re=1700$.

Burner Diameter Effect. Four burners of different diameter were chosen to provide data over a wide range of Froude numbers. The burners used had an inside diameter of 0.305, 0.584, 1.19, and 2.692 mm to provide Froude numbers from 1.65×10^5 to 1.14×10^8 for $Re=1700$ and $P=1\text{ atm}$. The effect of burner diameter on the mean angular deflection is shown in Figure 6. Note that the normalized axial and radial scales are different for each burner. Figure 6 shows that the breakpoint length decreased with an increase in the burner diameter. This result is an indication of the

significant buoyancy effect in the near burner region. With a smaller burner, the fuel-jet velocity and Froude number are higher, and hence the buoyancy is less significant. The breakpoint length is plotted versus the Froude number for the different burners in Fig. 7. The Froude number is plotted on a log scale. Evidently, the breakpoint length increases as the Froude number increases. These results show that transition from laminar to turbulent combustion is influenced by buoyancy.

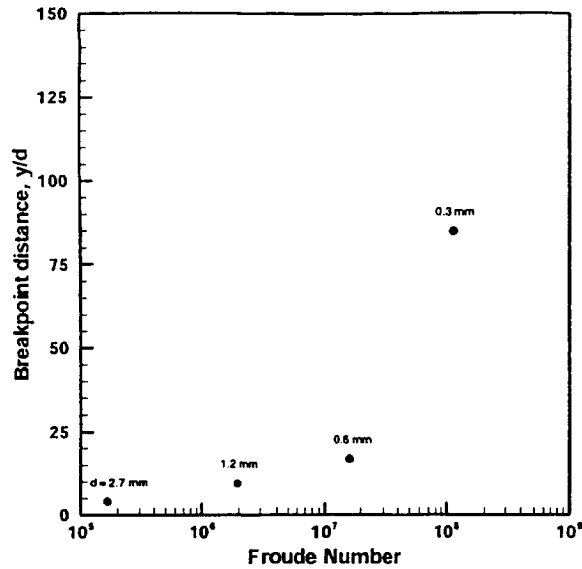


Figure 7. Breakpoint Length vs Froude Number Using Different Diameter Burners, $P=1.0$ atm, $Re=1700$.

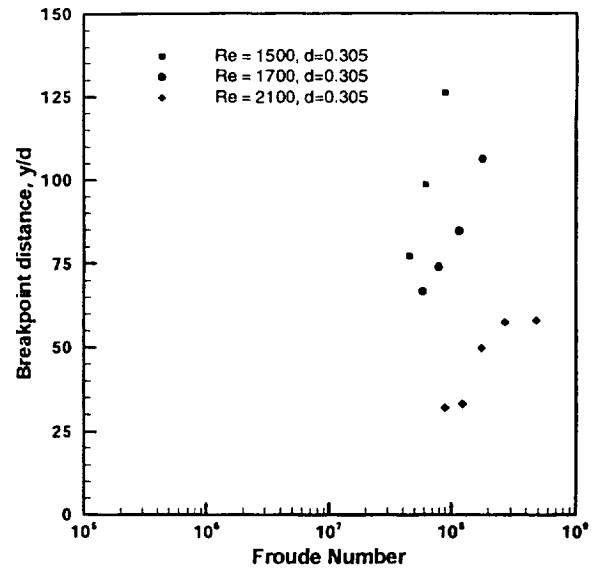


Figure 9. Breakpoint Length vs Froude Number Using Different Operating Pressures, $d=0.305$ mm, $Re=1700$.

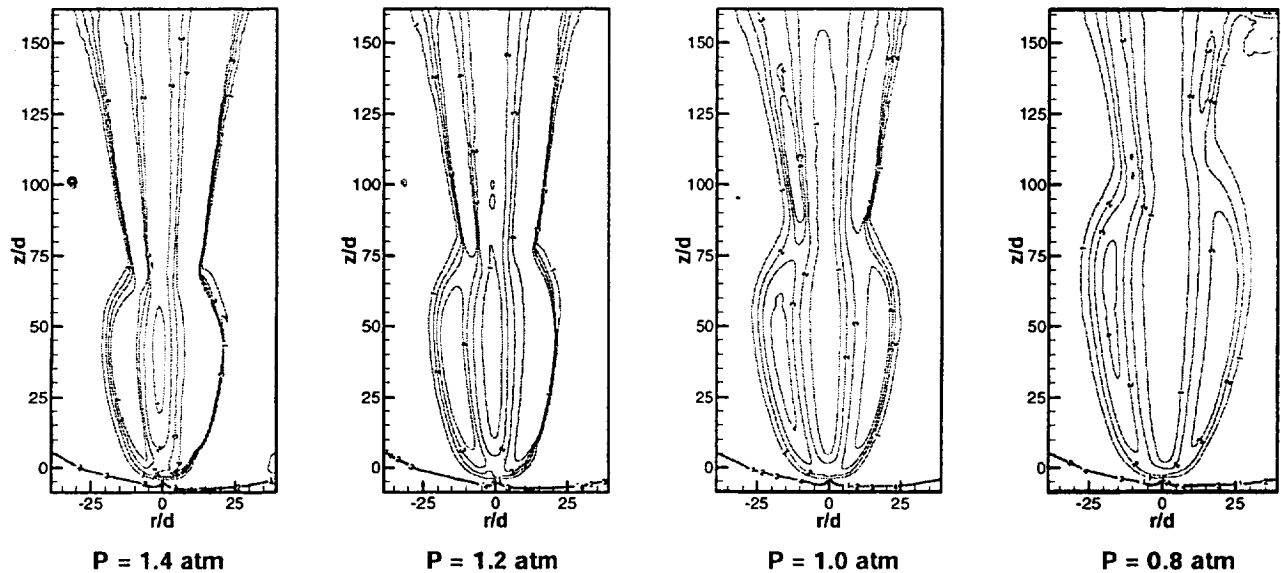


Figure 8. Effects of Operating Pressure on Contours of Mean Angular Deflection Contours, $d=0.305$ mm, $Re=1700$

Chamber Pressure Effect. Several combustion experiments have simulated buoyancy on the ground by varying the ambient pressure [12]. In the present study, the operating pressure was varied from 1.4 to 0.8 atm in decrements of 0.2 atm. Figure 8 illustrates the effect of pressure on mean angular deflection for $d=0.305$ mm and $Re=1700$. Results show that the flame transitioned farther downstream as the pressure was reduced. In addition, the flow width in the laminar region of the flame increased as the pressure, and hence, the buoyancy was reduced. These observations of buoyancy effects agree with experiments

of Al-Ammar [13] performed in microgravity using the 2.2-second drop tower. Figure 9 shows the effect of pressure, characterized by the Froude number, on breakpoint length at different Reynolds numbers for $d=0.305$ mm. The smallest diameter burner was chosen to obtain Froude numbers greater than 10^7 . For a given Reynolds number, the breakpoint length increased as the Froude number was increased. These results show that the Froude number is an important parameter for determining transition from laminar to turbulent combustion.

Conclusions

Experiments were performed in earth gravity to evaluate buoyancy effects on transition from laminar to turbulent combustion in hydrogen gas jet diffusion flames. The jet exit Froude number to characterize the buoyancy was controlled by varying the operating pressure and/or by using burners of different inside diameter. A nearly symmetric flow-field was obtained in the transitional flame by time-averaging data from the schlieren images. The location of the breakpoint, separating the laminar and turbulent portions of the flame, was identified from contours of rms angular deflection determined from schlieren images. Results show that the breakpoint length is affected by both the jet exit Reynolds number and the jet exit Froude number. The transition process was delayed at higher Froude numbers, suggesting the stabilizing effect of the non-buoyant environment. The study reveals buoyancy effects similar to those observed in drop tower experiments with transitional hydrogen jet diffusion-flames.

Acknowledgements

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References

1. Hottle, H.C., and Hawthorne, W.R., *Third Symposium (International) on Combustion*, The Combustion Institute, 1953, p. 254-266.
2. Coats, C.M. and Zhou, H., *Twenty-Second Symposium (International) on Combustion*, The Combustion Institute, 1988, p. 685-692.
3. Takeno, T., and Kotani, Y., *Progress in Astronautics and Aeronautics*, AIAA Inc., New York, 1978, vol. 58, p. 19-35.
4. Takahashi, F., Mizomoto, M., and Ikai, S., *Combustion and Flame*, 48:85-95 (1998).
5. Yule, A.J., Chigier, N.A., Ralph, S., Boulderstone, R., and Ventura, J. *AIAA Journal*, 19:752-760 (1981).
6. Clemens, N.T., and Paul, P.H. *Combustion and Flame*, 102:271-284, (1995).
7. Katta, V.R., and Roquemore, W.M., *Combustion and Flame*, 92:274-282, (1993).
8. Hegde, U., Zhou, L., and Bahadori, M.Y., *Combustion Science and Technology*, 102:95-113 (1994).
9. Albers, B.W., *Schlieren Analysis of Time Dependent Laminar and Transitional Gas-Jet Diffusion Flames*, Master's Thesis, University of Oklahoma, 1999.
10. Albers, B.W., and Agrawal, A.K., *Combustion and Flame*, 119:84-94 (1999).
11. Baum, R.T., McGrattan, K.P., and Nyden, M.S., *Combustion and Flame*, 113:358-372 (1998).
12. Agrawal, A.K., Cherry, S.M., and Gollahalli, S.R., *Combustion Science and Technology*, 140:51-68, (1998).
13. Al-Ammar, K., *Scalar Measurements and Analysis of Hydrogen Gas-Jet Diffusion Flames in Normal Gravity and Microgravity*, Ph.D. Dissertation, University of Oklahoma, 1998.